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THE DEPENDENCE OF THE OCCUPATION OF GALAXIES ON THE HALO FORMATION TIME

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ABSTRACT

We study the dependence of the galaxy contents within halos on the halo formation time using two galaxy formation models, one being a semianalytic model utilizing the halo assembly history from a high resolution N-body simulation and the other being a smoothed particle hydrodynamics simulation including radiative cooling, star formation, and energy feedback from galactic winds. We confirm the finding by Gao et al. that at fixed mass, the clustering of halos depends on the halo formation time, especially for low-mass halos. This age dependence of halo clustering makes it desirable to study the correlation between the occupation of galaxies within halos and the halo age. We find that, in halos of fixed mass, the number of satellite galaxies has a strong dependence on halo age, with fewer satellites in older halos. The youngest one-third of the halos can have an order of magnitude more satellites than the oldest one-third. For central galaxies, in halos that form earlier, they tend to have more stars and thus appear to be more luminous, and the dependence of their luminosity on halo age is not as strong as that of stellar mass. The results can be understood through the star formation history in halos and the merging of satellites onto central galaxies. The age dependence of the galaxy contents within halos would constitute an important ingredient in a more accurate halo-based model of galaxy clustering.

Subject headings: galaxies: formation — galaxies: halos — large-scale structure of universe — cosmology: theory — dark matter

1. INTRODUCTION

In the cold dark matter hierarchical model of structure formation, the formation and evolution of galaxies are coupled with those of dark matter halos. Studying the distribution of galaxies inside halos can aid us in the understanding of the galaxy formation process and in the interpretation of clustering properties of galaxies. In this Letter, we investigate the dependence of the galaxy contents on the halo formation time using numerical galaxy formation models.

Our study is closely related to recently developed models of galaxy clustering, namely, the framework of the halo occupation distribution (HOD) and the approach of the conditional luminosity function (CLF). Both models are based on statistical descriptions of the relation between galaxies and dark matter halos. The HOD characterizes the relation in terms of the probability distribution $P(N|M)$ that a halo of mass M hosts N galaxies of a given type, and the spatial and velocity distributions of galaxies within halos (Jing et al. 1998; Ma & Fry 2000; Peacock & Smith 2000; Seljak 2000; Scoccimarro et al. 2001; Berlind & Weinberg 2002; Cooray & Sheth 2002). Instead of $P(N|M)$ for galaxies of a given type, the CLF method uses the luminosity function of galaxies within halos as a function

of halo mass to establish the relation between galaxies and dark matter halos (Yang et al. 2003). HOD and CLF models have been applied to interpret the observed galaxy clustering in a number of surveys (e.g., Jing et al. 1998, 2002; Bullock et al. 2002; Moustakas & Somerville 2002; Yang et al. 2003; van den Bosch et al. 2003; Magliocchetti & Porciani 2003; Yan et al. 2003; Zheng 2004; Zehavi et al. 2004, 2005; Ouchi et al. 2005; Lee et al. 2005; Cooray 2005), and with the help of these models our understanding of galaxy clustering has been greatly improved and refined.

One key assumption in these halo-based models is that the *statistical distribution* of galaxies inside halos depends only on halo mass. This assumption has its theoretical origin in the excursion set formalism (Bond et al. 1991), which predicts that a halo's assembly history depends only on its mass. It is inherent in any semianalytic galaxy formation model that uses halo merger trees based on the excursion set formalism. Using the high-resolution Millennium N-body simulation, Gao et al. (2005) (also see Harker et al. 2005) show that the clustering of halos at a given mass has a dependence on the halo formation time, and the dependence becomes much stronger at halo masses $\ll M_*$, the nonlinear characteristic mass. Galaxy properties are expected to be correlated with the halo formation time, and to this extent, the environmental dependence of the halo formation time would lead to a dependence of the statistical distribution of galaxies inside halos on the environment as well as on halo mass. Once high accuracy modeling eventually becomes demanded by galaxy clustering data and/or by cosmological applications, the current HOD and CLF models may have to be modified to take into account the environmental dependence. Given the age dependence of the halo clustering, the study of galaxy contents as a function of halo age at fixed halo mass would shed light on

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the extension of the HOD/CLF model. Moreover, the dependence of galaxy properties on the halo formation time is an interesting problem on its own, since it can aid us in our understanding of the galaxy formation process.

In this Letter, we examine the dependence of the halo occupation properties of galaxies on the halo formation time, using a semianalytic galaxy formation model (SAM) and a smoothed particle hydrodynamics model (HYD). In § 2, we introduce the simulations and galaxy formation models. We show a confirmation of the age dependence of halo clustering in § 3. The dependence of galaxy properties on the halo formation time is the content of § 4, where we present our results in terms of the CLF as a function of halo mass and formation time. In § 5, we give a summary and discussion.

2. THE SIMULATIONS AND GALAXY FORMATION MODELS

Two main simulations are used in our study. The one that the SAM is based on is a P^3M N-body simulation in Jing & Suto (2002) with 512^3 particles in a cubic box of 100 h^{-1}Mpc. A spatially-flat ΛCDM model is adopted with density parameters $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$. We adopt the cold dark matter power spectrum of Bardeen et al. (1986) with a shape parameter $\Gamma = \Omega_m h = 0.2$ and the amplitude $\sigma_8 = 0.9$. The softening length is $10\,h^{-1}$kpc, and the particle mass is $M_p \sim 6.2 \times 10^8\,h^{-1}M_\odot$. We denote this simulation as SAM-ΛCDM. The galaxies of the SAM sample are generated by the model of Kang et al. (2005) that explicitly follows the assembly history of each halo in the simulation. The model successfully explains a wide variety of observational facts, including luminosity functions in different bands and the bimodal color distribution of galaxies.

The other simulation, denoted as HYD-Gadget2, is performed as smoothed particle hydrodynamics with the TREE-PM code Gadget2 (Springel 2005; Springel et al. 2001), following the evolution of 512^3 dark matter particles and 512^3 gas particles in a cubic box of 100 h^{-1}Mpc. It includes the physical processes of radiative cooling, star formation, and energy feedback from galactic winds (Springel & Hernquist 2003). The cosmological and initial density fluctuation parameters of the model are $(\Omega_m, \Omega_\Lambda, \Omega_b, \sigma_8, n, h) = (0.268, 0.732, 0.044, 0.85, 1, 0.71)$, and the transfer function is computed from CMBFAST (Seljak & Zaldarriaga 1996). The softening length is also $10\,h^{-1}$kpc, and the particle mass (dark matter+gas) is $M_p \sim 5.54 \times 10^8\,h^{-1}M_\odot$. Galaxies are identified as gravitationally bound groups of stars and cold gas particles that are associated with a common local maximum in the baryon density. We note that the effect of dust extinction, which is included in the SAM model, is not taken into account in this model.

In addition to the two main simulations, we also use a low-resolution simulation of 512^3 particles in a box of $300\,h^{-1}$Mpc only for the purpose of probing the age dependence of halo clustering at high halo mass. This simulation (denoted as 300-ΛCDM) has the same cosmological parameters as SAM-ΛCDM, and the particle mass is $M_p \sim 1.67 \times 10^{10}\,h^{-1}M_\odot$.

In all the simulations, halos are identified with the friends-of-friends algorithm (Davis et al. 1985) with a
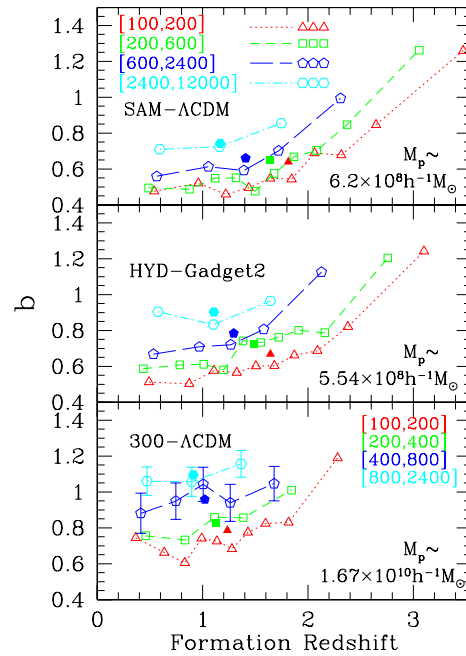

FIG. 1.— Halo bias factor as a function of formation time. The two integers in brackets indicate the range of particle numbers of halos (symbols have the same meaning in the two top panels). The particle mass is labeled as M_p in each panel. The open symbols connected by lines are the results in different age bins, while the filled symbols show the mean formation redshift and bias factor for all halos in the given mass bin. Poisson error bars are plotted for the two high-mass bins in the bottom panel.

linking length 0.2 times the mean particle separation.

3. THE DEFINITION OF FORMATION TIME AND THE AGE DEPENDENCE OF HALO CLUSTERING

We define the halo formation time as the time when its most massive progenitor has exactly half of the final mass, interpolated between two adjacent outputs if necessary. The progenitor of the final halo is defined as a halo in an earlier output that has more than half of its particles found in the final halo. If the most massive progenitor in an output has more than twice the mass of the one in the earlier adjacent output, we excluded the final halo in our study since its formation time is difficult to measure because its main progenitor was likely to be bridge-connected to a massive halo. In the end, about 10% of the halos are excluded.

We divide halos in each halo mass bin into several(3, 5, or 10) age bins with an equal number of halos in each age bin. The square of the halo bias factor is calculated by taking the ratio of the two-point correlation functions of halos and matter, averaged over scales $5\,h^{-1}$Mpc $< r < 20\,h^{-1}$Mpc.

The results of the dependence of halo clustering on the formation time are shown in Figure 1. We confirm the finding by Gao et al. (2005) that old halos cluster more strongly than young ones. In particular, at $\sim 10^{11}\,h^{-1}M_\odot$, the large-scale autocorrelation amplitude for the oldest 10% of the halos is more than 5 times that for the youngest 10% of the halos. For massive halos, the dependence becomes weak. Wechsler et al. (2005) find that the age dependence of the halo clustering reverses its trend for halos more massive than the nonlinear mass
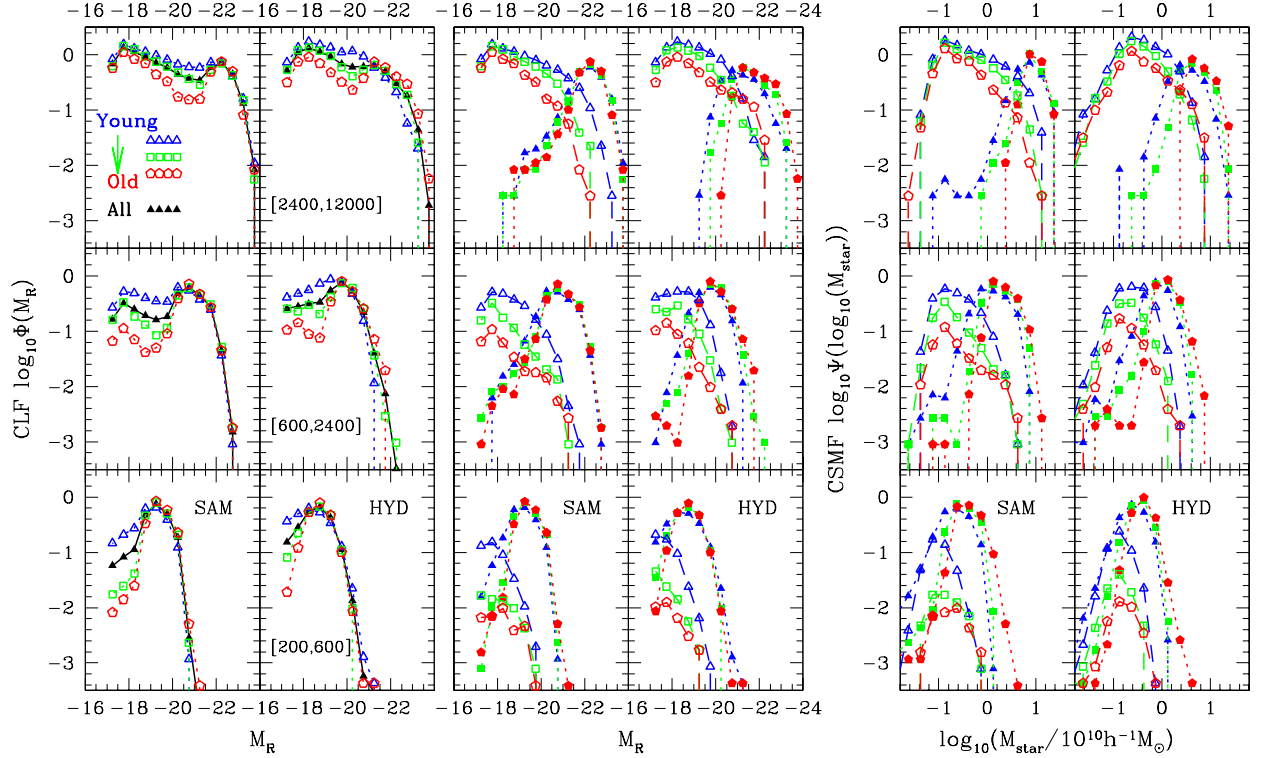
Fig. 2.— Conditional luminosity function (CLF) and conditional stellar mass function (CSMF) as a function of halo age. *Left two columns*: CLFs from the SAM (*left*) and HYD (*right*) galaxy formation models. Results are shown in three mass bins indicated by the particle numbers [the particle mass in the SAM (HYD) model is $M_p = 6.2(5.5) \times 10^8 \, h^{-1} M_\odot$]. *Central two columns*: Same as the left two columns, but the CLF is separated into contributions from central galaxies (*filled symbols*) and satellites (*open symbols*). *Right two columns*: Same as the central two columns, but for the CSMF. The CSMF is not complete at low stellar mass, which causes the steep drop at the low stellar mass end.

M_* (10^{13} and $4.6 \times 10^{12} \, h^{-1} M_\odot$ for the SAM-ΛCDM and HYD-Gadget2 simulations in our study), if halo concentration is used as an approximation of age. We do not detect such a clear trend, which could be buried in the large (Poisson) uncertainty as indicated in Figure 1 for the two high-mass bins.

4. THE AGE DEPENDENCE OF THE CONDITIONAL LUMINOSITY FUNCTION

In this section, we study the dependence of the occupation of galaxies on the halo formation time from the SAM and HYD galaxy formation models. The results are presented in terms of the CLF $\Phi(L|M)$, which is the expected number of galaxies per unit luminosity in a halo of mass M (Yang et al. 2003). Only galaxies brighter than $M_R = -17.0$ are considered in our study, where M_R is the R-band absolute magnitude.

The R-band CLFs from the SAM and HYD models are shown in the left two columns of Figure 2. The drop below $M_R \sim -18$ indicates that the CLFs are only complete for $M_R < -18$. For clarity, halos in each mass bin are only divided into three age bins with an equal number of halos in each age bin. A clear dependence of the CLF on halo age is found in both models, and the dependence becomes stronger at the faint end of the CLF. In general, there are more faint galaxies and fewer bright ones in younger halos. At the faint end, the youngest one-third of halos could host 10 times more galaxies than the oldest one-third. At the bright end, the trend of more bright galaxies in older halos is clear in the HYD model

in the two high-mass bins, and it tends to disappear at low halo mass ($\sim 10^{11} \, h^{-1} M_\odot$). For the SAM model, the trend at the bright end is not apparent. The subtle difference between the SAM and HYD models at the bright end could be due to the facts that the dust extinction effect is not included in the HYD model and that the gas cooling is switched off for halos of circular velocity larger than $350 \, \mathrm{km \, s^{-1}}$ in the SAM model.

In the central two columns of Figure 2, the CLFs are separated into contributions from central and satellite galaxies, as is done in Zheng et al. (2005). At the bright end, the CLF is dominated by the bump caused by central galaxies. In older halos, central galaxies appear to be brighter, and the central galaxy bump as a whole shifts to higher luminosity. There are two reasons for central galaxies being brighter in older halos. First, in older halos, star formation is triggered at an earlier time and may last longer. Second, the accretion of satellite galaxies into older halos happens earlier, and there is enough time for them to merge onto central galaxies. Both scenarios increase the amount of stellar components in the central galaxies of older halos. To show that this is indeed the case, we plot the conditional stellar mass function (CSMF) $\Psi(M_{\mathrm{star}}|M)$ in the right two columns of Figure 2, separating into contributions from central and satellite galaxies. The CSMF is not complete at the low stellar mass end ($M_{\mathrm{star}} < 10^9 \, h^{-1} M_\odot$), which explains the steep drop at this end. It can be clearly seen that central galaxies in older halos have more stars.

Young stellar populations are more luminous than old ones, and this reduces, but not completely erases, the luminosity difference in central galaxies of young and old halos. As a result, the difference in the central galaxy CLFs in halos of different ages is not as large as that in the central galaxy CSMFs. In the lowest mass bin, the HYD model may have more stars formed recently, which broadens the central galaxy CLF in young halos and minimizes the difference among the central CLFs in halos of different ages.

The faint end of the CLF, where the dependence on halo age becomes much stronger, is dominated by satellite galaxies. The correlation of the number of satellite galaxies with the halo formation time reflects the balance between the accretion and destruction processes (Gao et al. 2004; Zentner et al. 2005). We find that, at a fixed mass, halos that formed earlier start to accrete satellites (subhalos) earlier. Then these satellites have a longer time to experience the orbital decay caused by the dynamical friction and will more likely merge with the main central halos. Subhalos surviving at $z \sim 0$ are dominated by those accreted recently. Therefore, even though young halos accrete their mass later than old halos, they have much more *surviving* satellites.

Since the stellar masses in central and satellite galaxies have opposite dependences on the halo formation time, we may expect that the total stellar mass in a halo of fixed mass is a weak function of the halo age. Defining the total stellar mass in a halo as the sum for galaxies with $M_{\rm star} > 10^9 \, h^{-1} M_\odot$, we find that, in general, there are somewhat more stars in halos formed earlier, but the difference between the average stellar masses in the youngest and oldest halos is within a factor of 2.

5. DISCUSSION AND CONCLUSIONS

In this Letter, we investigate the dependence of the galaxy contents on the halo formation time using two galaxy formation models, one with a semi analytic method utilizing the realistic halo assembly history from N-body simulations and the other with a smoothed particle hydrodynamics simulation including radiative cooling, star formation, and energy feedback from galactic winds. Even though our techniques for building merger trees as well as our simulation methods are independent, we confirm the dependence of halo clustering on the formation time reported by Gao et al. (2005). We study the CLF and CSMF of galaxies as a function of the halo formation time and find that galaxies inside halos have a strong correlation with the halo formation time. In halos

that form earlier, there are fewer satellite galaxies, and their central galaxies appear to be more luminous, which can be understood through the early onset of star formation and the merging of satellites onto central galaxies. The dependence of the halo occupation number of satellite galaxies on the formation time in this study is similar to that of subhalos presented in Wechsler et al. (2005) (also see Zentner et al. 2005), which is not surprising since satellite galaxies reside in subhalos.

The HOD or CLF model assumes that the *statistical distribution* of galaxies inside halos depends only on halo mass. However, we note that this assumption does not mean that at fixed halo mass, the occupation number is independent of halo age. The correlation between the occupation number and the halo formation time exists even if the halo assembly history is based on the excursion set theory (e.g., Zentner et al. 2005), and the distribution of the halo age at fixed mass could provide the scatter that goes into the probability distribution of the occupation number at fixed halo mass [e.g., $P(N|M)$ in the HOD model]. It is the dependence of halo clustering on halo age that makes the above correlation potentially important in interpreting galaxy clustering data. Given the age-dependent halo clustering, the age dependence of HOD/CLF constitutes a key ingredient for a more accurate halo-based model of galaxy clustering. In view of this, a detailed study of the correlation between galaxy contents and halo formation time, like that performed in this Letter, is desired.

Depending on the application, the current version of the HOD/CLF model without taking into account the non-Markovian nature of halo formation, can still give accurate descriptions (e.g., Yoo et al. 2005). We reserve a detailed investigation for future work, to see to what extent it is adequate in different applications.

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